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14. ABSTRACT
Generalized multivariate analysis of variance and related reduced-rank regression are general statistical models that con versions of regression, canonical correlation, and profile analyses, as well as analysis of variance (ANOVA) and covariar univariate and multivariate settings. It is a powerful and yet not very well known tool. In [1] we develop a unified framewo explaining, analyzing, and extending signal processing methods based on GMANOVA. We show the applicability of this framework to a number of detection and estimation problems in signal processing and communications, and provide new ways to derive numerous existing algorithms for radar target estimation and detection; source location using parametric s models; synchronization and space-time channel and noise estimation; space-time symbol detection in; blind channel eq estimation, and signal seperation; spectral analysis nuclear magnetic resonance (NMR) spectroscopy.
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Statistical Signal Processing:

Generalized multivariate analysis of variance and related reduced-rank regression are general statistical models that comprise versions of regression, canonical correlation, and profile analyses, as well as analysis of variance (ANOVA) and covariance in univariate and multivariate settings. It is a powerful and yet not very well known tool. In [1] we develop a unified framework for *explaining, analyzing,* and *extending* signal processing methods based on GMANOVA. We show the applicability of this framework to a number of detection and estimation problems in signal processing and communications, and provide new and simple ways to derive numerous existing algorithms for

- radar target estimation and detection;
- source location using parametric signal models;
- synchronization and space-time channel and noise estimation;
- space-time symbol detection in
- blind channel equalization, estimation, and signal separation;
- spectral analysis nuclear magnetic resonance (NMR) spectroscopy

Many of the above methods were originally derived "from scratch," without knowledge of their close relationship with the GMANOVA model. We explicitly show this relationship and present new insights and guidelines for generalizing these methods. We also acknowledge the pioneering works of Brillinger (on frequency-wavenumber analysis, and Kelly and Forsythe (on radar detection, who first applied GMANOVA to signal processing problems. Our results could inspire applications of the general framework of GMANOVA to new problems in signal processing. We present such an application to flaw detection in nondestructive evaluation (NDE) of materials. A promising area for future growth is image processing.

Vector-Sensor Antennas:

Coupling between two collocated orthogonal circular thin-wire loops is analyzed in [2]. Classical theory of thin wire loops is used to obtain a general solution in matrix form for the Fourier coefficients of the loop currents. Analytical expression for currents induced through the mutual coupling is obtained for the case when all loop current harmonics higher than first can be ignored. It is found that strong coupling can exist for all loop current harmonics, except for the fundamental. It is also found that coupling for orthogonal collocated loop antennas depends on the relative locations of the loop terminals.

In [3] we propose an approach to achieve high-performance localization of multiple sources using an array of spatially-distributed electric and magnetic component sensors. The array comprises subarrays that are well calibrated individually but not with each other. Numerical examples demonstrate the efficacy of the proposed method.

Space Time Adaptive Processing for Radar:

In [4] we propose a novel parametric approach for modeling, estimation, and detection in space-time adaptive processing (STAP) systems. The proposed model is based on the Wold-like decomposition of 2-D random fields. It is first shown that the same parametric model that results from the 2-D Wold-like orthogonal decomposition naturally arises as the physical model in the problem of space-time processing of airborne radar data. We exploit this correspondence to derive computationally efficient fully adaptive and partially adaptive detection algorithm. Having estimated the models of the noises and interference components of the field, the estimated parameters are substituted into the parametric expression of the interference-plus-noise covariance matrix. Hence, an estimate of the fully-adaptive weight vector is obtained, and a corresponding test is derived. Moreover, we prove that it is sufficient to estimate only the spectral support parameters of each interference component in order to obtain a projection matrix onto the subspace orthogonal to the interference subspace. The resulting partially adaptive detector is simple to implement, as only a very small number of unknown parameters need to be estimated. The parametric interference mitigation procedure can be applied even when information in a single range gate is available, thus achieving high performance gain when the data in the different range gates cannot be assumed stationary. The performance of the proposed methods is illustrated using numerical examples.

Beamforming:

We present a new method of beamforming using the fractional Fourier transform in [5]. This method encompasses the minimum mean-squared error beamforming in the frequency domain or spatial domain as special cases. It is especially useful for applications involving chirp signals such as signal enhancement problems with accelerating sinusoidal sources where the Doppler effect generates chirp signals and a frequency shift, and active radar problems where chirp signals are used as the transmitted signal. Numerical examples demonstrate the potential advantage of this method over the ordinary frequency or spatial domain beamforming for a moving source scenario.

In [6] we considered the problem of designing linear beamformers to estimate a source signal $s(t)$ from sensor array observations, where the goal is to obtain an estimate $\hat{s}(t)$ that is close to $s(t)$. Although standard beamforming approaches are aimed at maximizing the SINR, maximizing SINR does not necessarily guarantee a small MSE, hence on average a signal estimate maximizing the SINR can be far from $s(t)$. To ensure that $\hat{s}(t)$ is close to $s(t)$, we proposed using the more appropriate design criterion of MSE. Since the MSE depends in general on $s(t)$ which is unknown, it cannot be minimized directly. Instead, we suggested beamforming methods that minimize a worst-case measure of MSE assuming known and random steering vectors with known second-order statistics. We first considered a minimax MSE beamformer that minimizes the worst-case MSE. We then considered a minimax regret beamformer that minimizes the worst-case difference between the MSE using a beamformer ignorant of $s(t)$ and the smallest possible MSE attainable with a beamformer that knows $s(t)$. As we showed, even if $s(t)$ is known, we cannot achieve a zero MSE with a linear estimator. In the case of a random steering vector we also proposed a least-squares beamformer that does not require bounds on the signal magnitude.

In the numerical examples, we clearly illustrated the advantages of our methods in terms of the MSE. For both known and random steering vectors, the minimax beamformers consistently have the best performance, particularly for negative SNR values. Quite surprisingly, it was observed that the least-squares beamformer, which does not require bounds on the signal magnitude, performs better than the recently proposed robust methods in the case of random DOAs. It was also observed that for a small difference between signal and interference directions of arrival, all our methods show better performance. The performance of our methods was similar when the signal was chosen as a deterministic sinewave or a zero-mean complex Gaussian random signal.

Channel Estimation and Communications:

Space-time channel estimation is essential for communication systems which separate sources in the space domain in addition to time/frequency/code domains. In [7], we first develop a Maximum Likelihood (ML) estimator for the spatial channel transfer function in the presence of strong interference sources, for 3 different channel scenarios: no multipath, locally scattered multipath, and general multipath case. As expected, the ML estimator, which assumes planar wave-field for the signal, provides superior performance over the ML solution for the general multipath case. In order to maintain the robustness to the scenario, an algorithm for scenario/model determination is developed, and its performance is evaluated via simulations.

We develop in [8] a frequency-domain channel estimation algorithm for single-user OFDM wireless systems in the presence of interference. In this case, the received measurement is correlated in space with covariance matrix dependent on frequency. Hence, the commonly used least-squares algorithm is suboptimal. On the other hand, accurate estimation of the spatial covariance matrix in such a model using the multivariate analysis of variance (MANOVA) method would impose significant computational overhead, since it would require large number of pilot symbols. To overcome these problems, we propose to model the covariance matrix using a-priori known set of frequency-dependent functions of joint (global) parameters, resulting in a structured covariance matrix. We find the unknown parameters using the estimated generalized least-squares (EGLS) which estimates the interference covariance parameters using a residual method of moments (RMM) estimator and the mean (user channel) parameters by maximum likelihood (ML) estimation. Since our RMM estimates are invariant to the mean, this approach yields simple non-iterative estimates of the covariance parameters while keeping the optimal statistical efficiency. Therefore, our algorithm outperforms the least-squares method in accuracy, and at the same time requires smaller number of pilots than the MANOVA method and thus has smaller overhead. Numerical results illustrate the applicability of the proposed algorithm. More recently we have extended these results to the asynchronous interference case in [9].

In [10], [11] we develop a semi-deterministic semi-stochastic channel model for the multiple-input multiple-output (MIMO) system under the macrocell environment with local-to-mobile and local-to-base scatterers. We show that employing closely-spaced antennas (e.g., phased array) at the base station is capable of achieving diversity via the local-to-base scatterers, which avoids impractical large aperture requirement for the spatial diversity at the base station. We evaluate the system performance in terms of ergodic capacity, average pairwise error probability (PEP), and signal-to-noise ratio (SNR); derive closed-form expressions for lower and upper bounds on the capacity and PEP; and show that the capacity, multiplexing and diversity gains are limited by the number of multipaths around the base station. The base-station array affects the lower bound on the capacity and the upper bound on the error probability through the same metric; thus, optimal design of the base station array based on this metric will optimize the two different information theoretic measures simultaneously. The fading correlation matrix also appears in the two bounds in the same form. To improve the performance of the macrocell MIMO system, we propose using artificial scatterers and discuss optimal design issues. Numerical examples demonstrate the accuracy of our analytical results and tightness of performance bounds.

Burst-mode receivers are key components of optical transmission systems including passive optical networks and have received much attention in recent years. In [12] we present new, efficient methods for burst optical signal detection and blind channel estimation in burst-mode data transmission using a modified K-means clustering technique. We also develop a data-aided feedforward symbol timing recovery method based on a polynomial interpolation and maximum likelihood estimation theory. A performance criterion considering the error caused by the interpolation approximation is derived for this method. The proposed detection and timing recovery approaches can be implemented effectively and rapidly; therefore, they are very suitable for burst-mode receivers. We also provide some numerical examples to demonstrate the performance of the proposed methods.

Transitions:

Researchers from SAIC are considering the construction of an array of EM vector sensors, following our introduction of this idea several years ago. Contact information: Mr. Ed Gjermundsen, Senior Staff Member, SAIC. Email: gjermundsene@saic.com. Phone: (703) 861-8711.

Motorola researchers are investigating the use of our OFDM channel estimation algorithms. Contact information: Dr. Timothy Thomas, who collaborated with us. Phone: (847) 538-2586. Email: T.Thomas@motorola.com

Graduated PhD Students:

We have graduated three PhD students:

- Aleksandar Dogandžić worked on sensor array processing in correlated noise. He has assumed an Assistant Professor position at Iowa State University. Dr. Dogandžic received a number of awards, in particular the Outstanding Thesis Award, UIC Division of Engineering, Mathematics and Physical Sciences, 2001, and the 2003 Young Author Best Paper Award, IEEE Signal Processing Society for [7].
- Yikun Huang, worked on optimal design of electromagnetic vector sensors including coupling effects, She is now Research Assistant Professor, ECE Department, Monatana State University.
- Aleksandar Jeremic, who worked on diverse topics, including channel estimation and biomedical imaging. He is now Assistant Professor, Department of Electrical and Computer Engineering, McMaster University.

Awards:

- Co-author of 2003 Young Author Best Paper Award, IEEE Signal Processing Society, for "Space-time fading channel estimation and symbol detection in unknown spatially correlated noise," with Aleksandar Dogandzic, *IEEE Trans. on Signal Processing,* Vol. SP-50, pp. 457-474, Mar. 2002.
- University Scholar Award, University of Illinois, since 2001.
- Elected Distinguished Lecturer, IEEE Signal Processing Society, 2004 to 2005.

Significant IEEE Services:

- Editor-in-Chief, *IEEE Transactions on Signal Processing,* January 2000 to December 2002.
- Vice President-Publications, IEEE Signal Processing Society, since 2003.
- Chair of the Publications Board, IEEE Signal Processing Society, since 2003.
- Member of the Board of Governors and Executive Committee, IEEE Signal Processing Society, since 2003.
- Founding Editor, Special Columns on Leadership Reflections, *IEEE Signal Processing Magazine,* since 2003.

Invited Keynote/Distinguished Lectures:

- Keynote Speaker, 3rd International Conference on Information, Communications and Signal Processing (ICICS2001), Nanyang Technological University, Singapore, October 17, 2001.
- Distinguished Lecturer, Third IEEE Sensor Array and Multichannel (SAM) Signal Processing Workshop, Sitges, Spain, July 19, 2004.

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